CORRELATION TECHNIQUE
IN
NUCLEATE BOILING

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INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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PARAMANAND SINGH

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TO

MY PARENTS

C E R T I F I C A T E

This is to certify that this work on "Correlation Technique in Nucleate Boiling" has been carried out under my supervision and it has not been submitted elsewhere for a degree.

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P.N. Singh

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NOMENCLATURE

$C(\tau)$	Correlation function
f	Frequency, cycles/sec.
f_s	Sampling frequency, samples/sec.
f_M	Maximum frequency, cycles/sec.
$f(t), g(t)$	Time varying functions
$\bar{f} - \bar{g}$	Time averages of the functions
$h(t)$	Impulse response function
M	Maximum number of correlation points
N	Number of Digitized samples
$P(f)$	Power spectral density
$P'(f)$	Smoothed power spectral density
t	time, sec.
T	Time period (= 1/f); integration time.
T_W	Temperature of the solid, i.e. of the wall and therefore of the liquid in contact with it.
T_L	Temperature of the bulk liquid
ω	Angular frequency equal to $2\pi f$, radian/sec.
Δt	Sampling interval, sec.
$\varnothing(\tau)$	Normalized correlation function
σ	Standard deviation
σ^2	Variance
τ	Time delay, sec.
ν	Auxiliary time variable.

σ_1	Surface tension of pure water.
σ_2, σ_3	Surface tension of water in increasing order of magnitude.

Subscripts:

ff	Auto-correlation
fg	Cross-correlation
i	Input
j	Index of summation
m	Maximum
N	Nyquist frequency
O	Output

ABSTRACT

Correlation technique has been used for analysing nucleate boiling. A simple experimental set-up has been developed to study the boiling phenomena. The analog signal obtained from the experimental set up is first converted to digital form using analog to digital converter of IBM 1800 DACS. The digitized signal is recorded on the magnetic tape and the computations are performed on IBM 7044 digital computer. As a first step, the correlation technique is used for obtaining the auto-correlation and power-spectral density for the single gas bubble. Correlation technique is much less time consuming than the conventional methods and has no probe to disturb the system. This technique can be used to investigate the effects of various parameters upon frequency response of the nucleate boiling. The qualitative effect of bubble multiplicity, the degree of sub-cooling and surface tension has been presented in this work. In the nucleate boiling experiment it is found that the size of the bubbles are too small for individual detection and the main contribution is due to the convective currents. The peak in the spectral density curve for nucleate boiling occurred at low frequency which can be attributed to the convective currents. More experiments are needed to make any conclusions regarding the nucleate boiling process.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Development in nuclear reactors and rocket engines where exceedingly high heat transfer rates occur in comparatively small areas, have focussed attention on boiling as a mode of transferring heat at high heat flux densities. To attain these high heat transfer rates by forced convection would require excessively high velocities with resulting high pressure drop. With nucleate boiling, however, they can be reached at much lower bulk velocities. Since there are so many variables which enter the boiling process, it has been difficult to find a heat transfer correlation that will satisfactorily predict boiling heat transfer under a variety of condition. Diverse models of the mechanism and the means of correlating the heat-transfer data have been presented in the literature. Comparisons of some models and their associated heat-transfer correlations reveal conflicting opinions concerning the mechanisms that explain the highly efficient heat transport of nucleate boiling. Fairly detailed summarizations of the various nucleate boiling models are presented in references 1 to 3.

In boiling three different regimes exist: nucleate, transition and film boiling. The change from one regime to

another is accompanied by marked changes in the hydrodynamic and thermal state of the system. These three regimes are shown in Fig. 1.1. When the temperature of the heating surface is below the fluid saturation temperature heat is transferred by convection, forced or natural, depending on the system. This region (AB, Fig. 1.1) has been extensively investigated and equations have been derived which permit the prediction of heat transfer rates. Nucleate boiling (BC, Fig. 1.1) starts when the temperature of the surface exceeds the saturation temperature by a few degrees. Adjacent to the surface a thin layer of superheated liquid is formed in which bubbles nucleate and grow from some preferred spots on the surface, such as solid particles or gas adsorbed on the surface. Thermal resistance of this superheated liquid film is greatly reduced by the agitation produced by the bubbles. An increase of the wall temperature is accompanied by a large increase of the bubble population causing in turn a sharp increase of the heat flux. However, as the temperature increases, bubbles become so numerous that their motions interact. Under these conditions the nucleate heat flux reaches its peak. Transition boiling begins if the temperature is increased further. In this region (CD, Fig. 1.1) no liquid-solid contact exists. The surface is blanketed by an unstable, irregular film of vapour which is in violent motion. In transition boiling an increase of temperature is

followed by a decrease of heat flux until a minimum value is reached at which point film boiling starts. This new regime is characterised by an orderly discharge of large bubbles with a regular frequency and at regular intervals. The mechanism of thermal radiation heat transfer becomes more significant as the wall temperature is increased. In the film boiling region the heat flux increases with an increase of temperature but at a much slower rate than in nucleate boiling. If attempts are made to attain large heat fluxes with film boiling, as high as those possible with nucleate boiling, the temperature of the heated surface may become so high as to result in the distruction of the heater. This is called a 'burnout'. Therefore, the highest rates of heat transfer can be attained in the nucleate boiling regime, taking care to remain below the 'departure from the nucleate boiling' point and avoiding the 'burnout' phenomena. Zuber [4] has discussed the regimes of boiling and analyzed both theoretically and experimentally, bubble growth and the hydrodynamic characteristics of nucleate pool boiling.

1.2 Review of Nucleate Boiling:

Various boiling models have been suggested as the reasons for the large heat-transfer coefficients of nucleate boiling. The principal models appearing in the literature

is presented below. In each of these models, one heat transfer mechanism is considered to be dominant.

<u>Bubble Agitation Mechanism</u>:

Considerable experimental evidence shows that an appreciable degree of fluid mixing occurs near the heater surface during boiling. This mechanism suggests that the growth and detachment of the bubbles (Fig. 1.2a) from a heated surface induces turbulence that promotes heat transfer between the surface and the liquid. The highly turbulent liquid transports heat into the bulk of the liquid. The bubble is a passive agent that keeps the fluid agitated but is never directly involved in the heat transfer process. Schlieren and Shadow-graph high speed motion pictures were made of the thermal boundary layer in the vicinity of the bubble by Hsu and Graham [5]. They found that the development of a bubble caused appreciable agitation in the thermal layer. As the bubble grew, it appeared to displace the thermal layer, and agitation was visible within the adjacent thermal layer as far as one bubble diameter from the center of the growing bubble. The surface area subject to this agitation is defined as the area of influence.

<u>Vapour-Liquid Exchange Mechanism</u>:

The vapour-liquid exchange mechanism (Fig. 1.2b) is a means of pumping a slug of hot liquid away from the wall

and replacing it with a cooler slug. The cooler slug picks up heat from the wall before being transported out into the bulk. A growing and departing bubble acts as the piston in this pumping process. This model resembles the bubble agitation model.

Evaporative Mechanism:

A third model (Fig. 1.2c) of nucleate boiling places emphasis on the evaporative process associated with the growth of the bubbles. The evaporative mechanism accounts for sizeable heat flux rate during nucleate boiling.

The inclusion of the concept of an evaporative mechanism at the base of a bubble necessitates the presence of a thin liquid layer. Such an assumption was made by Moore and Mesler [6] in proposing the presence of a micro-layer of liquid underneath the bubble. Experimental verification of the presence of micro-layer has been established by Hospeti and Mesler [7]. They used a chemical deposition technique involving calcium sulphate which contained radioactive sulfur 35. The radioactive sulfur made possible the measurement of the amount of deposit residue left by a sequential history of many bubbles developing at a particular site. Auto-radiographs of the deposits was related to the amount of liquid boiled off in generating the bubbles; thus,

estimates of the thickness of the liquid microlayer under the bubble could be made. For average heat fluxes ranging from 7000 to 20,000 Btu per hour per square foot, the microlayer thickness was observed to vary from 19×10^{-6} to 10^{-4} inch.

Sharp [8] employed three kinds of experimental techniques to detect the presence and magnitude of the microlayer. The simpler of the techniques was the use of an electrical continuity probe that was inserted into the base of a growing bubble. The indication of electrical continuity between the probe and the heating surface was interpreted as the presence of a thin liquid layer. The more sophisticated method involved the application of the optical principles of interference fringes to measure the thin microlayer. Sharp was able to make estimates of the local thickness of the microlayer at various radial positions beneath the bubble at several time intervals of bubble growth. The measured microlayer thickness varied between 4-16 μ-in. These values are somewhat smaller than those observed by Hospeti and Mesler, but it is remarkable that there is an overlapping range of general agreement. Sharp used the measured values of the depletion rate of the microlayer to predict an average heat flux rate underneath the bubble. The average rates varied between 30,000 and 50,000 Btu per hour per square foot for the area under the bubble.

Voutsinos [9] **has** investigated the growth and evaporation of the microlayer underlying a bubble forming on a glass heater surface using laser interferometry and high speed photography. The results for the single bubble indicated that the microlayer thickness is of the order of 5 μ-in. Subsequent analysis of these results confirms that the microlayer evaporation phenomena is a significant heat transfer mechanism, representing approximately 25 percent of the total nucleate boiling heat transfer rate.

Graham and Hendricks [10] have proposed a model of nucleate boiling where time and surface area averages of the following basic heat transfer mechanisms have been taken into consideration (i) transient thermal conduction through the liquid thermal layer in the vicinity of a nucleation site that is preparing to bear a bubble (ii) evaporation from a microlayer surface underneath a bubble that is attached to the heater surface (iii) turbulent-free convection that is taking place over the surface areas not covered by bubbles (A zone of enhanced convection occurs in the vicinity of a growing bubble). The overall model presented by Graham and Hendricks emphasizes that nucleate boiling should be thought of primarily as a series of transient heat-transfer processes over distinct regions of the surface.

Mikic and Rohsenow [11] assumed that the main mechanism of heat transfer in nucleate boiling is transient

heat conduction and subsequent replacement of the superheated layer around boiling sites associated with the bubble departure. They found that the heat flux versus wall superheat relation depends on the cavity size distribution of the boiling surface. Torikai and Yamazaki [12] studied boiling heat transfer mechanism by using the electro-conductive glass plate and high speed motion picture camera. They found three mechanism of boiling heat transfer: First mechanism is a heat conduction through the thin liquid film in contact area of bubbles on the heating surface, which is main part in heat transfer at the high superheating temperature in a wettable surface. Second mechanism is a heat transfer in natural convection by bubbles and in forced circulation of flow, which is dominant at low superheating temperature in any surfaces in saturation of liquid. Third mechanism is a heat conduction in unsteady state by contact of liquid on the heating surface during the detachment of bubbles, which is large part in heat transfer in sub-cooling liquid. Tong [13] has described the boiling mechanisms at various flow conditions and has given emphasis to the prediction of incipient nucleate boiling, effects of surface fouling, and transient cooling.

Ganic and Afgan [14] studied the bubble growth in pool boiling by following the growth of the bubble by the use of high-speed photography and simultaneously measured the temperature in the bubble and its liquid environment by a fast response thermocouple. They measured the continuous

temperature distribution around a single bubble by changing the position of the thermocouple probe and analyzed a large number of bubbles.

Nail [15] used a scanning Electron Microscope (SEM) to examine pool boiling nucleation sites on 304SS in contact with distilled degassed water. Nucleation sites were located during the boiling process by noting the coordinates of the bubble locations on the surface. He magnified these locationsusing the SEM and made photographs of nucleation sites. The radii of the cavities varied from 14.8 μ-in to 180 μ-in. and width of groves varied from 75 μ-in. to 154 μ-in.

An experimental program of transient boiling under low pressure condition was initiated by Schultz et al [16] to study the single artificial cavities of known geometry and size. The technique employed to characterize the temperature field relies on experimental heating period of such short duration that convection effects can be neglected and the temperature distribution computed analytically using a pure conduction model. They examined the role of the developing transient thermal boundary layer on the stability of the just nucleated vapour bubble through the use of the analysis of high speed close-up films of the growing nucleus.

Rogers and Mesler [17] used a special surface thermocouple and measured large temperature fluctuations during nucleate boiling of water on chromel P surface. They found that the temperature dropped 20 to 30°F in about 2 msec. but required 10 to 20 msec to recover. They postulated that surface is cooled during initial bubble growth by evaporation of a microlayer into the bubble. To test this hypothesis they developed a technique to photograph a bubble growing from an artificial site as the surface temp. was measured. They found that the result is in consistent with their hypothesis.

Theofanous and Patel [18] have observed that the initial to final vapour density ratio (when significantly greater than one) strongly influences vapour bubble growth rate in the inertia and the inertia/heat transfer regimes.

Since boiling heat transfer is controlled by generated bubbles on the heating surface, to understand the nucleate boiling a better knowledge of bubble is desirable. Many aspects of the study of bubbles, such as formation of bubbles, bubble shape, growth rate, motion of the bubble maximum size, and forces acting on a bubble have been studied by many investigators [19-25]. By far the most frequently employed technique in the study of boiling has been the analysis of high speed motion pictures. A frame by-frame analysis of the pictures provides the two-dimensional

projected size and the local velocity of the bubbles. The main disadvantages of this approach are that the analysis is very time-consuming and yields only a two-dimensional representation of the bubble.

1.3 Correlation Technique:

Correlation procedure takes two functions of time x(t) and y(t), delays one of the functions by an amount τ, then multiplies them together and averages the result over some finite time. If x(t) = y(t) an 'autocorrelation' function is involved; if x(t) and y(t) are different, a 'cross-correlation', function is obtained. When x(t) = y(t), the resulting auto-correlation function $C_{ff}(\tau)$ is symmetric about $\tau = 0$, with $C_{ff}(0)$ greater than or equal to any other value of $C_{ff}(\tau)$. In practice, there is usually a sharp maximum at $C_{ff}(0)$ so that one is able to distinguish $C_{ff}(0)$ clearly from any other value. In accordance with the Wiener theorem, the power density spectrum is obtainable as a cosine Fourier transform of auto-correlation function. This is the only means by which power density spectrum of random function is calculated. Thus, the correlation technique is the application of correlation to the spectral analysis of the random phenomena. This technique can also be used for the spectral analysis of periodic and aperiodic function (Ref. 26,27).

Since nucleate boiling is a random process, the techniques of noise analysis should be useful in the study of the process. The first investigation of boiling water nuclear reactors utilizing noise analysis techniques was performed by Argenne National Laboratory [28]. Transfer functions, spectral moments and correlation functions were obtained for the BORAX-IV reactor.

McKnight and Ram [29] used correlation technique to determine the power spectra and auto-correlation for a single gas bubble rising in water and for a nucleate boiling system. Both analog and digital method of getting power spectral density were used. In analog method, the signal was squared and integrated over a measured time interval and this information was used to calculate the power spectral density. In digital method, the auto-correlation curve obtained by using a signal correlator, was digitized and the Fourier analysis was performed using these digitized points. These functions were then analyzed to determine the bubble size, velocity and frequency of generation. They also showed that how the heat flux, the degree of subcooling and surface tension of the liquid affect the power spectrum of the nucleate boiling system.

McCurdy [30] showed the relationship between the spectral density of the spatially-averaged temperature

(of a heated filament) and the auto-and cross-spectral densities of the temperature induced at individual sites. By analyzing the trace of the spatially-averaged temperatures of the system, he obtained its spectral density. Using correlation technique , he investigated nucleate pool boiling in saturated and subcooled water in normal and low gravity fields and obtained the power spectra of the temperature fluctuations at the nucleating surface. The spectra of the surface temperature fluctuations were found to contain a number of peaks, occuring at the same frequencies with which bubbles were emitted from the various active sites on the heating surface, as determined from the high-speed films. The spectrum of the temperature fluctuations was markedly influenced by the degree of subcooling and by an inverse gravity field. McCurdy found that generalized harmonic analysis is a useful tool for the study of heat transfer phenomena which possess a random character such as the temperature fluctuations which occur in nucleate boiling.

Csermely and Ostrander [31] have used the correlation technique for determining the frequency response function of a heat exchanger. They used a concentric tube water-to-water counter flow heat exchanger which was subjected to temperature perturbations at the tube-side inlet. The perturbations were produced by a discrete interval binary

noise signal. Correlation and spectral analysis for obtaining the frequency response was accompanied by means of IBM 1620 digital computer with the tube inlet and shell outlet temperature histories on the punched paper tape as the computer input. The frequency response function determined by the correlation technique was found to be in reasonable agreement with the frequency response function obtained by the more conventional step and pulse-input technique.

Determination of the frequency-response function of a system by correlation technique has the advantage over the other techniques that interference of signals with noise is reduced in the end results. This technique should be used whenever noise is a problem. Correlation technique[29] can be used to obtain information previously obtained by using time-consuming motion picture methods, specifically, that the two-dimensional projected size of the bubble, its local velocity, and the size and frequency distributions of the bubbles can be determined.

1.4 Present Work:

The present work consists of utilizing correlation (Noise) techniques for detecting and analyzing nucleate boiling. Correlation techniques have the advantages of

i) Consuming less time for analysis,

ii) No probe to disturb the process,

iii) Easy measurement of the power spectrum

iv) Different parameters affecting the process can be correlated.

v) High degree of precision even in the face of severe input noise to signal ratio.

Correlation techniques though based on simple principles, are usually complex in the sense that digital computing machines or special electronic circuits are used.

Here, as a first step single gas bubbles are analyzed for their auto-correlation and power spectral density and later nucleate boiling is studied.

In the present work, correlation technique uses digital method for calculating the auto-correlation and power density spectrum of the signal. The digitization of analog signal has been accomplished by an analog-to-digital converter (ADC) using IBM 1800 DACS. The digitized data has been recorded on the magnetic tape. The computations have been carried out on an IBM 7044 digital computer. Output from IBM 7044 are recorded on magnetic tape, and this tape has been later brought back to IBM 1800 for final plotting of the results.

Chapter 2 of the thesis deals with the background theory of the correlation. Here the computation of the correlation function from experimental data on the basis of time averaging has been discussed. Also described in this Chapter are the alternative methods for data acquisition and analyzing the analog signal.

Chapter 3 contains the description of the physical layout of the system, system hardware and software. In the software, the functions of the various computer program and sub-routines used for recording and analyzing the data have been discussed.

Chapter 4 describes some of the results obtained by this method for single bubble as well as some preliminary results of nucleate boiling. Results of the surface tension variation on single bubble as well as nucleate boiling have been presented.

Chapter 5 concludes with some recommendation for future work, especially to study the nucleate boiling phenomenon.

CHAPTER 2

THEORY

2.1 Discussion of Analytical Method:

In many areas of science and engineering, the accuracy of experimental measurements is limited by the signal to noise ratio of the system. This fact has led to the development of the field of information and statistical communication theory. Harmonic analysis technique has been generalized to include randomly varying signals (noise) with the aid of Fourier transform. This generalization is quite important because random signal or noise, contain information describing the character of the system from which they emanate. Random signal analysis (noise analysis) has been used in many diverse fields, such as nuclear engineering, communication, radio astronomy, scismology, neurology etc. The brief treatment of random signals (noise analysis) which is included in this chapter follows essentially that of Thie [32].

Correlation Functions and Power Spectral Density Functions:

Consider some physical process which gives rise to a time-varying signal f(t). The signal may be simple or complex periodic or have the character of noise, that is, be random varying. Auto-correlation of a signal f(t) is

obtained by taking the time average of $f(t)\ f(t-\tau)$, where $f(t-\tau)$ is the same signal delayed by time τ. Mathematically, the auto-correlation function $C_{ff}(\tau)$ is defined as,

$$C_{ff}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} f(t) \cdot f(t-\tau)\, dt \tag{2.1}$$

where T is the period of the signal.

Important properties of auto-correlation function $C_{ff}(\tau)$:

1) $C_{ff}(\tau)$ is an even function of τ i.e. $C_{ff}(\tau) = C_{ff}(-\tau)$.

2) $C_{ff}(\tau)$ has maximum value for zero delay time ($\tau = 0$).

i.e. $C_{ff}(0) \geq C_{ff}(\tau)$

3) $C_{ff}(\tau)$ is independent of the time origin. This means that auto-correlation function of $f(t)$ is the same as that of $f(t-t_o)$ where t_o may have any value.

4) For real $f(t)$'s, $C_{ff}(\tau)$ is a real function of τ.

Applying property (1) of the auto-correlation function, equation (2.1) can be written as,

$$C_{ff}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} f(t) \cdot f(t+\tau)\, dt \tag{2.2}$$

For the case in which the signal $f(t)$ is given as N discrete data points (electronically by digitizing an analog signal, $f(t_j)$), the auto-correlation function may be determined by replacing the integral in eqnation (2.2) by a summation as,

$$C_{ff}(\tau) = \lim_{N \to \infty} \frac{1}{N} \sum_{j=1}^{N} f(t_j)\, f(t_j+\tau) \tag{2.3}$$

The normalised auto-correlation function is defined with respect to deviation from the mean and is given by,

$$\phi_{ff}(\tau) = \lim_{T\to\infty} \frac{1}{2\sigma_f^2\, T} \int_{-T}^{T} [f(t)-\bar{f}].[f(t+\tau)-\bar{f}]\, dt$$

$$= \lim_{N\to\infty} \frac{1}{\sigma_f^2\, N} \sum_{j=1}^{N} [f(t_j)-\bar{f}].[f(t_j+\tau)-\bar{f}] \tag{2.4}$$

where $\bar{f}$ is the mean value of the time-varying signal over one period of a periodic signal or over the discrete number of digitized values of a random signal, and σ_f^2 is the variance of the signal $f(t)$. Strictly speaking, the auto-correlation function is computed in the limit of $N \to \infty$ or $T \to \infty$, but in practice, however, one treats a finite amount of data and computes C_{ff} for τ's upto

$$\tau_m = M\Delta t < N\, \Delta t$$

for N data points spaced by Δt.

$$\phi_{ff}(\tau) = [\frac{1}{N-\tau/\Delta t} \sum_{j=1}^{N-\tau/\Delta t} (f_j-\bar{f})(f_{j+(\tau/\Delta t)} - \bar{f})]/\sigma_f^2 \tag{2.5}$$

where,

$$\bar{f} = \frac{1}{N} \sum_{j=1}^{N} f_j$$

and,

$$\sigma_f^2 = \frac{1}{N} \sum_{j=1}^{N} (f_j - \bar{f})^2$$

$$\phi_{ff}(\tau) = \left[\frac{1}{N-M} \sum_{j=1}^{N-M} (f_j - \bar{f})(f_{j+(\tau/\Delta t)} - \bar{f})\right] / \sigma_f^2 \qquad (2.6)$$

The auto-correlation function $C_{ff}(\tau)$ and the normalized auto-correlation function are related by,

$$C_{ff}(\tau) = \sigma_f^2 \, \phi_{ff}(\tau) + (\bar{f})^2 \qquad (2.7)$$

Similarly, if two signals, f(t) and g(t), either an input and an output or two outputs to a known input, are obtained from a system, and one is delayed and the average value of the product of signals is determined, then the result is the cross-correlation function of the two signals. This may be written as,

$$C_{fg}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} f(t).g(t+\tau) \, dt \qquad (2.8)$$

As with the auto-correlation function, one can define the normalized cross-correlation function as,

$$\phi_{fg}(\tau) = \lim_{T \to \infty} \frac{1}{2\sigma_f \, \sigma_g T} \int_{-T}^{T} [f(t) - \bar{f}].[g(t+\tau) - \bar{g}] \, dt \qquad (2.9)$$

and for N synchronized data points spaced Δt apart for both signals, the normalized cross-correlation function may be calculated for τ upto $\tau_m = M\Delta t < N\Delta t$ as,

$$\phi_{fg}(\tau) = \left[\frac{1}{N-\tau/\Delta t} \sum_{j=1}^{N-\tau/\Delta t} [f_j-\bar{f}][g_{j+(\tau/\Delta t)} - \bar{f}] \right] / \sigma_f \, \sigma_g \tag{2.10}$$

where,

$$\bar{f} = \frac{1}{N} \sum_{j=1}^{N} f_j$$

$$\bar{g} = \frac{1}{N} \sum_{j=1}^{N} g_j$$

$$\sigma_f^2 = \frac{1}{N} \sum_{j=1}^{N} (f_j-\bar{f})^2$$

$$\sigma_g^2 = \frac{1}{N} \sum_{j=1}^{N} (g_j-\bar{g})^2$$

The cross-correlation function can be described as representing the degree of conformity between two signals.

The correlation functions are useful in describing a system's response in the time domain. The impulse response function h(t) of a system is related to the input $f_i(t)$ and output $f_o(t)$ by the following convolution integral,

$$f_o(t) = \int_{-\infty}^{\infty} f_i(\nu)\, h(t-\nu)\, d\nu \tag{2.11}$$

Using this relation, the correlation functions defined in equations (2.2) and (2.8) can be written as,

$$C_{io}(\tau) = \int_{-\infty}^{\infty} h(\nu)\, C_{ii}(\tau-\nu)\, d\nu \tag{2.12}$$

where $C_{ii}(\tau)$ and $C_{io}(\tau)$ are the auto-correlation of the input

and the cross-correlation between the input and the output respectively. If the input is purely random, then $C_{ii}(\tau-\nu)$ is a delta function, which indicates that the cross-correlation is related to the impulse response function $h(\nu)$.

Wiener Theorem for Auto-Correlation:

Wiener theorem for auto-correlation states that auto-correlation function of a random function and the power density spectrum of the random function are related to each other by a Fourier cosine transformation as given by,

$$C(\tau) = \int_{-\infty}^{\infty} P(f) \exp(i\omega\tau)\, df , \qquad \omega = 2\pi f$$

$$= 2 \int_{0}^{\infty} P(f) \cos \omega\tau \, df \qquad (2.13)$$

where $P(f) = \lim_{T\to\infty} \frac{1}{T} |g(f)|^2$

$$P(f) = \lim_{\tau_m\to\infty} \int_{-\tau_m}^{\tau_m} C(\tau) \exp(-i\omega\tau)\, d\tau$$

$$= \lim_{\tau_m\to\infty} 2\int_{0}^{\tau_m} C(\tau) \cos \omega\tau \, d\tau \qquad (2.14)$$

With N discrete values of $C(\tau)$ spaced Δt apart, the power density spectrum can be expressed as(Ref. [29]):

$$P(f) = \frac{1}{N} C(o) + \frac{2}{N} \sum_{j=1}^{M} C(j\Delta t) \cos 2\pi f j\Delta t$$

$$= \Delta t\, C(o) + 2\Delta t \sum_{j=1}^{M} C(j\Delta t) \cos 2\pi f j\Delta t \qquad (2.15)$$

In the computer program described in the next chapter, eqn. (2.15) has been used for calculating the power density spectrum.

2.2 Data Recording and Analysis:

There are two general methods of recording and analysis, of the data.

1) Analog or continuous and
2) Digital or Discrete

The former may involve the use of analog computers if done off-line. If done on-line, the term continuous is appropriate because the electronic analyzers use the filters, amplifiers, and integrators that handle continuous function of time. Digital data handling is invariably done off-line because a digital computer is involved. It is quite possible that analog and digital methods may be used in a single experiment.

Continuous recording may be accomplished by standard chart recorders or by magnetic tape recording. Having once recorded an experimental data on magnetic tape, it can be rerun and reanalyzed at any time and as often as desired. Data so recorded is easily stored and is compatible with both analog and digital methods of analysis. Also by using different recording and playback speeds, one can achieve various time transformations in the analysis. Recording

continuous signals on magnetic tape may be done in two ways a) Direct amplitude recording in which the degree of magnetization is proportional to the signal, (b) Frequency modulation of a carrier directly recorded at constant amplitude. Though the first has been highly successful in audio frequency (20 cps to 20,000 cps) application, the second is used in data recording because frequency response to low frequency is needed.

When digital analysis of a continuous signal is desired, an analog to digital conversion must be performed. The rate at which the conversion of analog signal to digital signal is done is decided by the sampling theorem. The theorem states that if a low pass band limited signal of bandwidth f_N is sampled at the rate greater than $2f_N$ samples per second, then the original signal can be completely determined from the sampled signal. Sampling time Δt is then related to the limiting frequency as,

$$\Delta t = \frac{1}{2f_N}$$

or,

$$f_N = \frac{1}{2\Delta t} = \frac{1}{2(\text{digitizing interval})} = \frac{N}{2T}$$

where the sampling frequency f_N is called the Nyquist frequency or cut-off frequency. Frequencies above f_N cannot be detected and therefore the numerical integrations have f_N

as the highest limit. In the event frequencies above the Nyquist frequency are actually present in the continuous signal, then a phenomena known as 'aliasing' occurs, that is, in the digital analysis these higher frequencies will appear below the Nyquist frequency and will be indistinguistable from the lower frequencies. To avoid difficulties from this source, one should choose f_s so that it exceeds the maximum frequency for which the spectral density is significant. If f_M is this maximum frequency, then requiring,

$$f_s \geq f_M$$

means that the sampling interval Δt should satisfy,

$$\Delta t = \frac{1}{2f_s} \leq \frac{1}{2f_M}$$

In words, the time interval between successive samples should be such that the sampled data contain atleast two samples per cycle of the highest frequency. In practice, ten to twenty samples per cycle of this highest frequency are used when noise is present.

If the auto-correlation function is determined upto $\tau_m = M\Delta t < N\Delta t$, then the highest frequency will be $f_N = M/2\tau_m$. This means the spacing of the frequencies $\Delta f = 1/2\tau_m$ or $1/2M\ \Delta t$. However, the spectral resolution due to a finite duration of sampling, T, is equal to 1/T or $1/\tau_m$. This limitation results since the auto-correlation

function is not known for $\tau > \tau_m$. Because of this one defines a spectral lag window for infinite τ's.

$$h(\tau) \leq 1 \quad \text{for} \quad |\tau| \leq \tau_m$$

$$= 0 \quad \text{for} \quad |\tau| > \tau_m$$

There are a variety of spectral windows, $h(\tau)$, which can be used to minimize the effect upon P(f) of contribution outside the range $f \pm \Delta f$.

Two frequently used windows are,

$0.5 + 0.5 \cos \frac{\pi\tau}{\tau_m}$ Hanning

$0.54 + 0.46 \cos \frac{\pi\tau}{\tau_m}$ Hamming

Since the power spectra obtained by eqnation (2.15) are spaced by $1/2\tau_m$, one of the above windows is used for smoothing them. In present work, power spectral density and the smooth power spectral density are calculated by using the following expressions [29],

$$P(f) = \Delta t\, C(0) + 2\Delta t \sum_{j=1}^{M} C(j\Delta t) \cos 2\pi f_j \Delta t \qquad (2.16)$$

$$P'(f) = 0.25\, P(f - \frac{1}{2\tau_m}) + 0.50\, P(f) + 0.25P\,(f + \frac{1}{2\tau_m}) \qquad (2.17)$$

Equation (2.17) has been used to write computer program which calculates smooth power spectral density from power spectral density obtained by the use of equation (2.15).

CHAPTER 3

EXPERIMENTAL SET-UP AND ANALYSIS

3.1 System Description:

The complete investigation procedure can be broadly be divided into two main parts:

(1) Hardware Development, and

(2) Software Development

Before describing details of the experimental set-up and data logging procedure, a block diagram representation of the system will be outlined. System representation is given in Fig. 3.1 where all the functional elements of the complete scheme are depicted.

In general, the process under investigation does not yield information which can be processed directly without the use of transducers. The transducer converts the message to an analog signal, a time varying electrical quantity, such as voltage or current, which is better suited for further processing by the data processing system.

For convenience and clear understanding, these things have been isolated as distinct identities, though in an actual system the separation may not be so obvious. Also shown are some of unwanted noise or disturbances which are inherent in any set-up.

Though, the description and details of each ~~bmr~~ block will be given separately, a look at the block diagram gives the signal flow information.

A parallel beam of white light (Block 1, Fig. passes through the transparent glass of the boiling sy. (Block 2, Fig. 3.1), having a bent copper tube with a hole in it to produce the bubble by passing gas or bubbles generated from a heated surface. The light beam is attenuated by bubbles rising through the medium. Fluctuation in the light signal caused by scattering of light by bubble is detected by a photo-multiplier tube which acts as an input transducer (Block 3, Fig. 3.1), converting the light signals to electrical pulses. Linear amplifier (Block 4, Fig. 3.1), amplifies this weak signal and transmits through coaxial cable acting as the transmission medium (Block 5, Fig. 3.1), to the interface equipment of the data processor. Transmission medium also sometimes called channel is an electrical connection in between the linear amplifier and input interface (Block 6, Fig. 3.1) bridging the distance between the source and data processor while maintaining the true characteristics of the signal. In this case the transmission medium is a coaxial cable of 75 ohms total impedence. Transmitted signal is fed to the input interface and filter where unwanted noise signals picked up during transmission are suppressed and the output of the filter is connected to solid state

multiplexer of IBM 1800 (Block 7, Fig. 3.1). This analog signal is converted into digital signals by an analog to digital converter (ADC) within the IBM 1800 system. Digitised signal values are recorded on the magnetic tape of IBM 1800, using software to be discussed later. Selective samples of data are processed on IBM 1800 for a quick analysis of the data and the majority of the samples have been processed by IBM 7044 (Block 8, Fig. 3.1). Signal was analysed for its auto-correlation and power spectral density. Since there was no plotter available in IBM 7044, output was put on a magnetic tape and brought back to IBM 1800 for final plotting of the results. Details of the hardware components is described below:

3.2 Hardware Development:

The experimental set-up consists of the following components:

(1) Light source

(2) Water tank

(3) PMT and Linear Amplifier

(4) Transmission Medium

(5) Input Interface and Filter

Light Source:

The optical set-up details has been shown in Fig.3.2. A 12 V, 3 mA tungsten filament bulb was used as the light

source. Power was supplied by a 30 volt power supply unit which was adjusted to give the desired voltage. A reflector was provided to focus the beam in one direction and avoid scattering of light. This light beam was passed through a G.I. pipe of diameter 4.2 cm and at the other end of the pipe a convex lens of focal length 25.7 cm was placed. Distance between the light source and lens was so adjusted that the light source falls exactly at the focal length of the lens to give a parallel beam of light. The whole set-up is enclosed in an aluminium box covered from top to protect from extraneous light. The beam is collimated through a hole of 6.5 mm diameter in the front to allow a narrow beam of light comparable to bubble size to come out of the box.

Water Tank:

Since experiment is performed in two parts (a) with gas bubbles (Fig. 3.2a), (b) nucleate boiling bubbles (Fig. 3. 3), two different test containers are used.

Test Container for Gas Bubble:

Fig. 3.3 shows the pictorial view of the container. This consists of a simple glass jar of 37.5 cm x 8 cm. This jar is filled with demineralised water to a height of 26 cm. Bubbles are generated in the jar from an orifice in a

copper tube submerged in the jar. An air cylinder was used to pass air through the copper tube. Bubble multiplicity and frequency of emission is changed by varying the flow of gas through the orifice. Glass container is wrapped in black paper to protect from unwanted light except for small portion to transmit the light signal.

Water Tank for Nucleate Boiling:

In the study of nucleate boiling the bubbles are formed by heating a copper rod pointed at the tip. The test piece is pointed to have preferably single nucleation site. However, this goal is partially achieved during the experiment, since it is observed that nucleation is occurring on the surface other than the tip. Fig. 3.4 shows the dimensions of the test piece. This test piece is heated externally by nichrome heater ribbon. To have a good thermal insulation, the copper piece is passed through a push fit teflon plug before fitting it at the centre of the water tank. Heat flux variation is achieved by varying the voltage across the nicrom ribbon.

Fig. 3.5 shows the constructional details of the water tank. The water tank filled with demineralized water to a height of 11.5 cm is provided with glass windows on two sides for allowing the light to pass through the tank. The dimensions of the water tank are 45.5 cm x 30 cm x 44.5 cm

which is very large compared to the 6.35 mm dia. of the test piece to minimize the effect of convection currents. Heating of water in the tank is achieved by two external heaters of 1 KW each, mounted at the bottom of the tank on either sides of the test piece. Different constant bath temperature is achieved by varying the supply voltage to the heaters by means of a variac. It has been observed that for a given water level in the tank, and a given voltage to heaters, a particular constant maximum bath temperature is obtained. A series of experiments with varying heater voltages are performed keeping the level of water constant, and when the temperature reached a steady state value, it is noted down. Voltage vs. temperature graph is plotted and this information is used in conducting the nucleate boiling experiment. The temperatures are recorded using a alcohol thermometers, the bulb of the thermometer is kept at 1.5 cm away from the tip and very near to the surface of the tank.

Photomultiplier Tube:

Photomultiplier tube (PMT), is the most important component of the whole system. This senses the fluctuation in the light signal and converts it to electrical signal. PMT is essentially a current source.

PMT used in this experimental set is RCA 6810A. This is a 14-stage, 2" dia. head-on type of photomultiplier tube. The photocathode material is Cs-Sb. 6810A features high

quantum efficiency, fast time resolution characteristic, low dark current, and high current amplification characteristic. The spectral response of 6810A covers the range from about 3000 to 7000 angstroms (Å). Maximum response occurs at approximately 4000 Å. Therefore, it has high sensitivity in the blue and less sensitivity in the red regions of the visible spectrum. 6810A is relatively insensitive to the effects of extraneous magnetic and electrostatic field. Maximum operating voltage for this tube is 2400 volts DC only. However, in our case it is much below this maximum rating. Voltage divider arrangement and basing diagram has been shown in Fig. 3.6 and 3.7.

Linear Amplifier:

Since the output of PMT is very small, it becomes very essential to amplify the signal before coupling it onto the transmission line.

Amplifier described in Fig. 3.8 consists of 3 stages: (i) Operational amplifier (a) is input buffer having unity gain. Input impedence of this stage is kept very high to match the impedence of the PMT. A gain of 1000 is achieved by 2 stage amplification (b) and (c). Transistor Q_1 and Q_2 are current amplifier to drive the coaxial line having very low input impedence. The overall band-width of amplifier

stage is kept upto 1 KHz as the signal expected is in low frequency region. After amplification, signal amplitude is in the range of 0.25 - 3.5 volts to be compatible with ADC input of IBM 1800.

Transmission Medium:

The output of linear amplifier is transmitted to IBM 1800 by means of a coaxial cable of 75 ohms total impedence. Coaxial cable is chosen to minimize the noise pick up during the transmission, since the signal carrying cable is quite often run close to the source of main voltage.

Input Interface and Filter:

In course of electrical signal transmission certain unwanted and undesirable effects take place, namely attenuation, distortion, interference, and noise. Attenuation reduces the signal strength. In this case attenuation is very negligible, since signal is transmitted over a very small distance. Distortion is signal alteration due to imperfect response of the system to the desired signal itself. Interference is contamination by extraneous signal. Noise is random and unpredictable electric signals which come from natural causes both internal and external to the system. when such random variations are added to an information bearing signal the information may be partially masked or totally obliterated.

Keeping above facts in view, Input interface and filter is designed to suit the signal at the receiving end.

It consisted of two stages as shown in Fig. 3.9.

First Stage: acts as input interface. High input impedence unity gain amplifier is used. Matching is achieved by resistance network at input of amplifier.

Second Stage: acts as a tunable filter, to cut off all signals of 50 c/s pick up and other undesirable frequency. Approximate values of resistors and capacitors are indicated in Fig. 3.9.

A short description of IBM 1800 is given before giving the details of data logging programme.

IBM 1800 Data Acquisition and Control Simulation (DACS):

IBM 1800 DACS is capable of accepting one or more analog inputs. Analog signals representing the physical phenomenon are to be amplified and fed to the analog to digital converter (ADC) of the 1800. When more than one signal is to be processed simultaneously a multiplexer scans the signals sequentially. There can be as many as 1024 analog input terminals attached to one ADC. Out of these, only 256 terminals can be solid state.

There are two types of multiplexer available. One is Relay multiplexer and the other is Solid state. The Relay

multiplexer accepts an analog signal which is differential in nature and is within ± 5 volts dynamic range. The multiplexer scanning frequency from one signal to another is 100 cps maximum. Solid state multiplexer can be used for high speed data acquisition. The signal attached to these terminals should have one terminal grounded, and accepts signals of ± 5 volts. Solid state multiplexers have a scanning frequency of 20,000 points per seconds.

The ADC of IBM 1800 has the ability to converting bipolar analog signals within ± 5 volts range to digifal values. It includes a buffer amplifier and has program selectable resolutions of 8, 11 and 14 bits. The larger the bit value the higher the accuracy and more conversion time. The conversion time for 8 bits, 11 bits and 14 bits resolutions are 29 μ sec, 36 μ sec, and 44 μ sec. respectively.

The input impedence of ADC is of the order of 10 megaohms.

Data word of the ADC:

The data word developed in the ADC is compatible with IBM 1800 word format. Each word starts with a bit alloted for the positive/negative sign and ends with a bit reserved for the overflow indication. The output of the ADC is in the binary form which is stored in the memory.

TSX and MPX Executive Programs:

For IBM 1800 DACS, there are two programming systems available viz., Multiplexing Executive (MPX) and Time-Sharing Executive (TSX). TSX program divides the entire core area into two parts, the skelton and V-core. In the skelton area all the important system programs and subroutines and a few frequently used user's program are permanently stored. The skelton area occupies approximately 8 to 10 thousand words of memory. IBM 1800 has 16 K memory. Therefore remaining memory (about 6 K) is available to the user under TSX system.

The MPX program divides the entire memory into several segments known as Areas. All the important system programs and subroutines are permanently stored in the skelton area occupying approximately 12 K words. Rest of the memory is divided into segments to execute programs of different execution priorities. MPX requires large core memory, at least 24 K word. The MPX system, generated at this installation with bare minimum facilities takes 11100 words of core, leaving only around 6000 words for users.

3.3 Software Development:

Data Logging:

The data logging program is given in Appendix A. The data logging program consists of sub-programs which can be modified to give different sampling rates and variable number of samples. The programs are also flexible and new subroutines can be added and/or deleted, if desired, to make the data logging program very versatile.

Since the maximum frequency components of the bubble signal expected is around 40 - c/s, a sampling rate of 80 would have served the purpose. But the sampling rate chosen for data logging is 250 sample/sec. in this case. Signal is sampled for 8.152 sec. to give 2048 samples. The digitized data in the binary form is finally stored on a magnetic tape. Since there is only one tape unit available some operater intervention becomes inevitable for changing the magnetic tape.

The data logging program is a link program. The link is needed to accommodate the main program and sub-programs in the memory of IBM 1800.

There are two links for data logging program.

FIRST LINK : DTLG1 DTLG1 (main program)

SAMP

ZSRCH

KALEN

TSAVE

WAIT

SECOND LINK OUTPT OUTPT (main program)

IPLOG

WAIT

DTLG1: The main program of the first link controls the sequence of operations to be performed. Depending on the status of 16 data switches (DATSW), control is passed from one subroutine to another.

SAMP: This subroutine is most important among all sub-routine because this decide the sampling time and starts the A/D converter to acquire data of a specified record length.

ZSRCH: This subroutine is executed only once in the beginning of the programme. This subroutine searches for the last logged data on the tape and makes the tape ready for recording

more data.

KALEN: The data logging program keeps track of time, date and month. This is achieved by the subroutine KALEN. Time, date and month must be entered when executing the data logging program. During the logging period the subroutine KALEN keeps updating the time, date and month.

SUMRY: At the end of data logging, a summary of what has been put on the tape is very much essential. SUMRY subroutine is called after the end of the data logging, and this gives the serial no. of the data logged, status of the data switches and the time. Data switches represent the information regarding the condition of the system, number of data points, gain of the system etc. which is recorded on the tape.

TSAVE: This subroutine serves the function of unloading the tape to save the recorded information.

WAIT: This subroutine comes in action whenever the data switch 3 is put in UP position. The data logging is suspended till the data switch 3 is in UP position. Since the UP position of data switch 3 can keep the computer in wait position, the experimenter can change the signal condition at the transmission end, without stopping the data logging program. As soon as the data switch 3 is put DOWN, the data logging once again starts.

OUTPT: This main program of the second link, is called when plotting of the signal is desired. A typical signal from the tape can be selected for plotting. OUTPT selects the required data for plotting and calls IPLOG.

IPLOG: This forms a subroutine of OUTPT. OUTPT calls subroutine IPLOG to make plots of the data requested. After plotting, control is returned to OUTPT again for further decision.

Sampling Rate:

For getting the sampling rate of 250 samples/sec. the signal has to be sampled at 40 msec. interval. The procedure for achieving this sampling rate is described below.

While reading an analog input, the flow chart shown in Fig. 3.10 has been used. The time elapsed between two sample is equal to the time taken by the program to execute the instructions from A to B and back to A. This time is found to be 39.85 msec. by trial and error. To obtain the required interval of 40 msec, some redundant instructions have to be introduced in the return path. These instructions are

```
LOOP  MDX  2  -1
      BSC     LOOP
```

These two instructions take 10 μsec. for execution. These instructions are executed repeatedly to obtain the desired delay of .15 msec.

Few salient features of the data logging program are:

(1) Number of points to be recorded on the magnetic tape is variable and can be entered through the data switches.

(2) Program can be kept in standby position for any amount of time, during which experimental conditions at the transmitting end can be changed. This avoids the starting of the system again and again during data logging.

(3) There always exists the possibility that the signal amplitude may incidently exceed the limit of ADC ($\pm$ 5 Volts) and in this case the ADC will not show the appropriate value of the signal. Before recording any data on the tape DTLG1 checks for the limit ($\pm$ 5 volts). If the signal amplitude is more than $\pm$ 5 volts, the data is treated to bad and not put on the tape. Thus DTLG1 recognises the bad and good sample.

(4) Any record on the magnetic tape which is suspected to be bad or gives trouble while reading can be erased and fresh data can be logged thereafter.

<u>Program for Analysis of the Data:</u>

Initially it is thought that the analysis can be done by IBM 1800, and a program is developed for processing the

data by IBM 1800. This program has been given in Appendix B. But later it is found that IBM 1800 gives dimensionality problem even after making many links and using small subroutines and takes more time as compared to IBM 7044. Program given in Appendix B works well for limited number of auto-correlation points. Since IBM 7044 is much more faster than IBM 1800, and has large memory, a program 'PROCS' for analysing the data by 7044 is developed. This is given in Appendix C. The program 'PROCS' has eight subroutines and few system subroutines.

Main program PROCS	READTP
	TREAD
	AUTO
	PSD
	SMUTH
	GRAF1
	ISKEL
	NPNCH

PROCS: Main program PROCS dictates the input/output scheme. PROCS can be operated in two modes. First mode is the Continuous mode, in the sense that every data on the input magnetic tape is analysed, and the second mode is the Selective mode where only selected data are analysed. PROCS can give paper output, punch output or output on magnetic tape according to the user's requirement. In this

case the output is mainly taken on magnetic tape which is later brought back to IBM 1800 for plotting the result.

READTP: Since the word format of IBM 1800 and IBM 7044 are different, conversion is needed for reading the IBM 1800 magnetic tape for IBM 7044. Subroutine READTP establishes the linkage between IBM 1800 and IBM 7044 and thus READTP is very essential subroutine without which processing of IBM 1800 magnetic tape on which data was logged is not possible.

TREAD: Subroutine TREAD brings required number of words from the magnetic tape to the computer memory. TREAD does so by cross referencing the subroutine READTP.

AUTO: Subroutine AUTO uses simple algorithm (Eq. 2.6) for computing the auto-correlation of the data points.

PSD: This subroutine calculates spectral density of the signal by taking the Fourier Transformation of the Auto-correlation function. Eqn. (2.15) has been used in writing the computer program.

SMUTH: This computes the smooth power spectral density of the signal. Eqn. (2.17) has been used in writing the computer program.

GRAF1: This subroutine is used for plotting the output Discrete plotting of points drawn by IBM 7044 is not as good as the continuous plot drawn by IBM 1800. A plot is taken

on IBM 7044 to just check the output.

ISKEL: Before recording the final output on magnetic tape all values are converted to integer form and scaled such that no values exceeds 32760 (limitation set by IBM 1800). This integer transformation is required because the program developed to read this tape in IBM 1800 handles only integer data on the tape and moreover, integer mathematics is faster and simpler to deal with.

NPNCH: Output in the form of punch card can be had by calling this subroutine.

Main program PROCS is very flexible and gives lot of options for the user. During the course of computation it is possible to know that upto which serial number the computation has been done.

Plotting the IBM 7044 Output by IBM 1800 Plotter:

The program for plotting IBM 7044 output by IBM 1800 has 3 subroutines. Program is given in Appendix D.

Main Program P7044: RITAP

TREAD

PLOT

TSAVE

P7044: For one experimental condition 4 or 5 records are selected and their auto-correlations and smooth power spectral density are averaged over 4 or 5 records and the averaged value of the auto-correlation and smooth power spectral density is plotted. This is done to compare the average value and the value obtained by taking single record.

RITAP: It has been mentioned earlier that the word format of IBM 1800 and IBM 7044 is different, once again a link has to be established in IBM 1800 and IBM 7044. Subroutine RITAP serves this purpose.

TREAD: This subroutine brings the required number of words from magnetic tape to the memory of IBM 1800 by cross-referencing the subroutine RITAP.

PLOT: The subroutine PLOT when called by P7044 draws the required plot and returns the control to P7044.

TSAVE: At the end of run, subroutine TSAVE unloads the tape and requests the user to save it.

3.4 Experimental Procedure:

Experiment is performed in two parts (a) with gas bubbles, (b) with nucleate boiling bubbles.

(a) Gas Bubbles:

In this case the bubbles are generated by passing air through a bent copper tube with a hole of 1.5 mm dia in it. The copper tube is dipped in the glass jar having demineralized water. Rate of bubble formation is controlled by adjusting the air flow rate through the copper tube. The whole set up is alligned such that the collimated beam of light, after intercepting the bubbles forming in the glass jar, falls on the photo multiplier tube. The PMT senses the fluctuation in the light intensity and converts it to the electrical signal. After proper amplification the signal is coupled on the transmission medium and at the receiver end, the signal is fed to the input interface and filter where unwanted frequencies are cut off. Output of the filter is connected to the ADC of IBM 1800. Data acquisition is initiated after appropriate selection of the record length and sampling frequency. The digitized data are recorded on the magnetic tape. The few data are processed on IBM 1800 and the majority of the data are processed on IBM 7044. Auto-correlation and smooth power spectral density are plotted on IBM 1800 plotter.

Choice of Parameters:

Bubble multiplicity and frequency of emission is controlled by varying the gas flow rate through the copper

tube. The effect of surface tension is studied by adding soap solution to the water. However, only the qualitative study of the variables are done in the present work.

(b) Nucleate Boiling:

In the nucleate boiling experiment, the bubbles are formed in the water tank on the tip of the copper rod heater. Rest of the procedure is same as the gas bubble experiment.

Choice of Parameters:

1) Degree of Sub-cooling:

Variation in the degree of sub-cooling is achieved by varying the bulk temperature of the water in the water tank, and the bulk temperature variation is obtained by varying the voltage to the auxiliary heaters.

The voltage applied to the auxiliary heaters is incremented in steps of 40 volts, the lower limit being 140 volts and the upper limit being 220 volts. Thus four different bulk temperature is obtained.

ii) Heat Flux to the Copper Rod Heater:

For each setting of the bath temperature four different heat flux conditions are obtained for the copper rod heater by varying the voltage using a variac. Minimum applied voltage to the copper rod is 30 volts and maximum

applied voltage is 90 volts. The increment in voltage is done in steps of 20 volts.

iii) Surface Tension:

To study the effect of surface tension on the auto-correlation and power spectral density, soap solution is added to the water (Bulk temp: $85.5^{\circ}C$, voltage applied to copper rod heater 90V). However, only qualitative study is done in the present work.

CHAPTER 4

RESULTS

4.1 Data Reduction and Presentation of Results:

The correlation technique has been used to determine the auto-correlation and power spectral density of gas bubbles and nucleate boiling bubbles. The auto-correlation has been calculated at 1000 points. The auto-correlation is normalized to zero delay time. It was found that by taking 4 or 5 records for averaging the effect of noise has been diminished and the accuracy is improved considerably. Normalized auto-correlation and smoothed power spectral density are averaged over 4 to 5 records and the average value of the functions are plotted against delay time and frequency respectively.

4.2 Gas Bubble:

Fig. 4.1a and 4.1b shows the auto-correlation and smoothed power spectral density plot for single gas bubble. σ_1, denotes the normal surface tension of the water. Peaks occur at the frequency of generation of the bubbles, and at the harmonics of that fundamental frequency. In Fig. 4.1b the first peak occurs at 5.1 cps. The amplitude of the second harmonic is very small compared to the fundamental frequency.

Figs. 4.2, 4.3 and 4.4 show the effects of surface tension variation on auto-correlation and spectral density. Here the surface tension σ_1, σ_2 and σ_3 are in the increasing order of magnitude. It is observed that as the surface tension is increased more and more peaks appear in spectral density curve towards the higher frequency.

Many records for single bubbles are analyzed and it is found that when the flow rate is small, single peaks characterizing only one distribution of bubble size appeared in the spectral density curve. Figs. 4.5a and 4.5b show the auto-correlation and smoothed power spectral density curve for multibubbles when the air flow rate through the copper tube is increased. Here the peaks occur at different frequencies with considerable amplitude indicating the splitting of the bubbles with increased flow rates.

The total area under each of the spectral density curve is physically related to the power content of the signal. Many spectral density curve with various flow rate are analyzed and the area under the spectral density curve are calculated. It is found that area under the spectral density curve increases as the flow rate increases. Unfortunately, quantitative results could not be given since the flow rate measurements are not done.

4.3 Nucleate Boiling:

Fig. 4.6 to 4.8 show the auto-correlation and spectral density plots for different degree of sub-cooling and different heat flux to the copper rod heater. Surface tension effect has been shown in Fig. 4.9.

In the nucleate boiling case, the size of the bubbles are too small for individual detection and the main observation is due to the convection currents. Since the size is small one expects spectrum to show peaks at high frequencies but however, the signal is weak compared to the convective currents signal which is of low frequency. The peaks at low frequencies are due to the convective currents. Analysis becomes difficult at these low frequencies and one has to use frequency modulation to record such signals.

CHAPTER 5

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

5.1 Conclusions:

The correlation technique has yielded auto-correlation and power spectral density of the gas bubble in reasonable agreement with the expected results. As the flow rate is increased bubble frequency increases and the area under the spectral density curve also increases showing the more power content associated with the signal. As the surface tension is increased more and more peaks appeared in the spectral density curve towards the higher frequency.

In the case of nucleate boiling, the size of the bubbles emerging from the copper rod heater are too small and so the signal amplitude is very small as compared to the convective currents. In this case the peaks occurred at low frequency due to convective currents and the analysis became difficult. In the nucleate boiling, it was not possible to get the single bubble from the copper rod heater, and hence the behavior of the single bubble could not be studied.

5.2 Suggestions for Future Work:

1. Generation of single bubble is a problem in the case of nucleate boiling, and a better method for generating single bubble should be used.

2. A better method for detecting the single bubble should be used, because the bubbles generated in nucleate boiling are too small.

3. Filaments where several sites occur detection should be selectively done for one site.

4. In presence of the strong convective currents, where the signal amplitude is comparatively low, frequency modulation method for recording the signal should be used.

5. Adjustable slits should be placed on both sides of the tank in order to collimate the light beam at the desired width.

Possible Application of the Findings:

Detection of the incipience of nucleate boiling in the reactor core can be done remotely using this technique. This could be accomplished by placing the light source at one end of the coolant channel and PMT or some other detection probe at the other end.

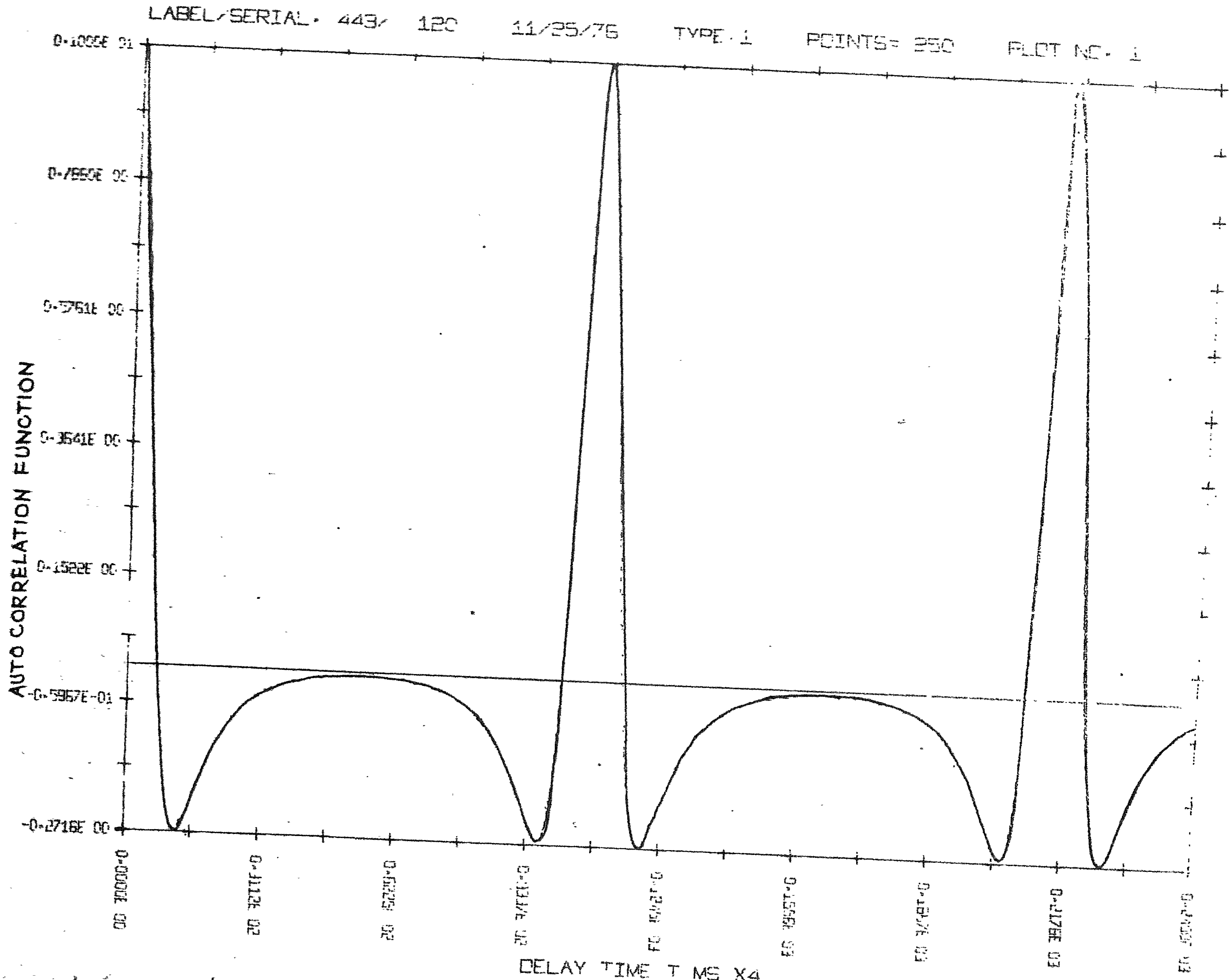

FIG. 4.1a AUTO CORRELATION, SINGLE BUBBLE, SURFACE TENSION σ_1 11/25/76

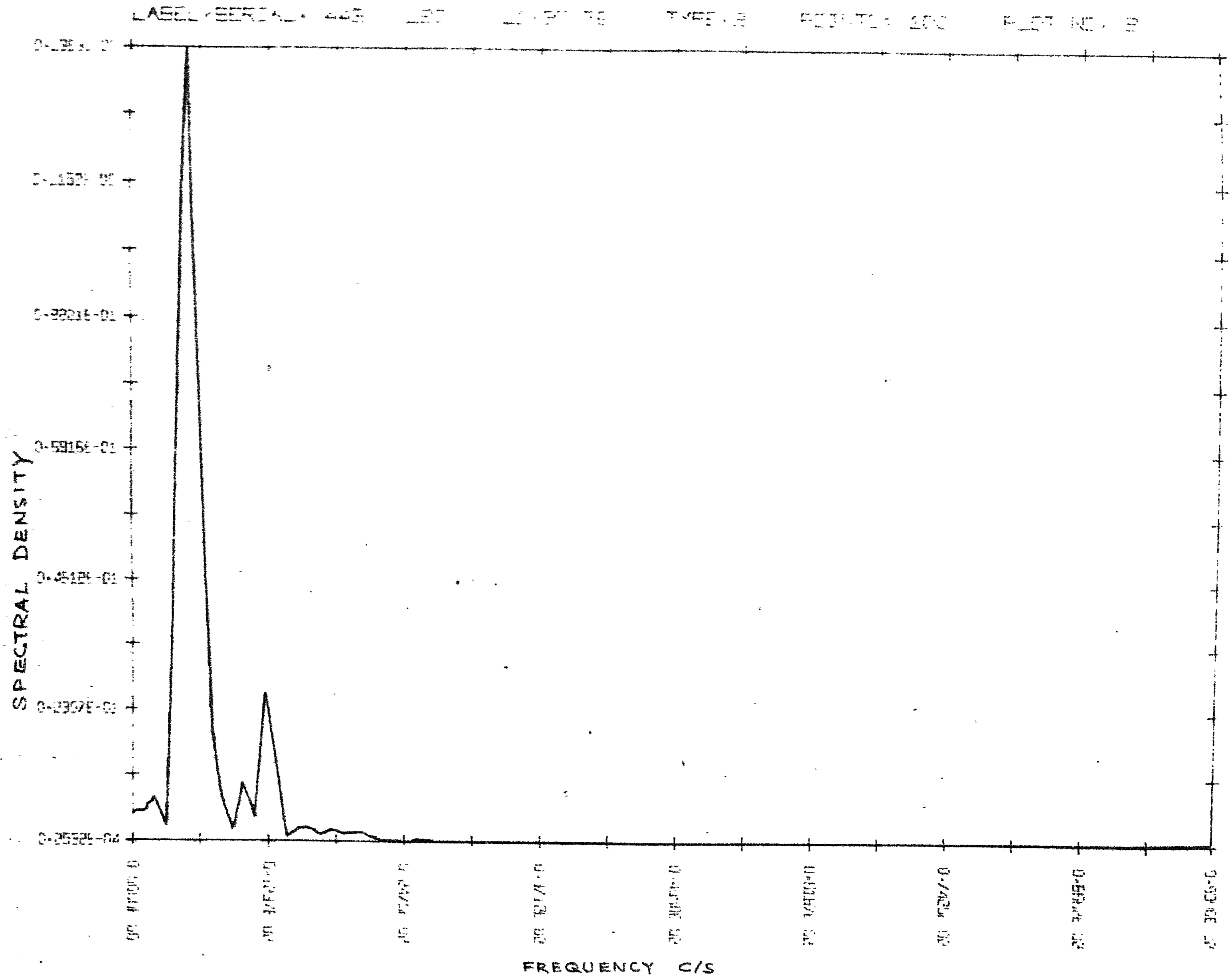

FIG. 4.1b SMOOTHED SPECTRAL DENSITY, SINGLE BUBBLE, SURFACE TENSION, 11/25/76

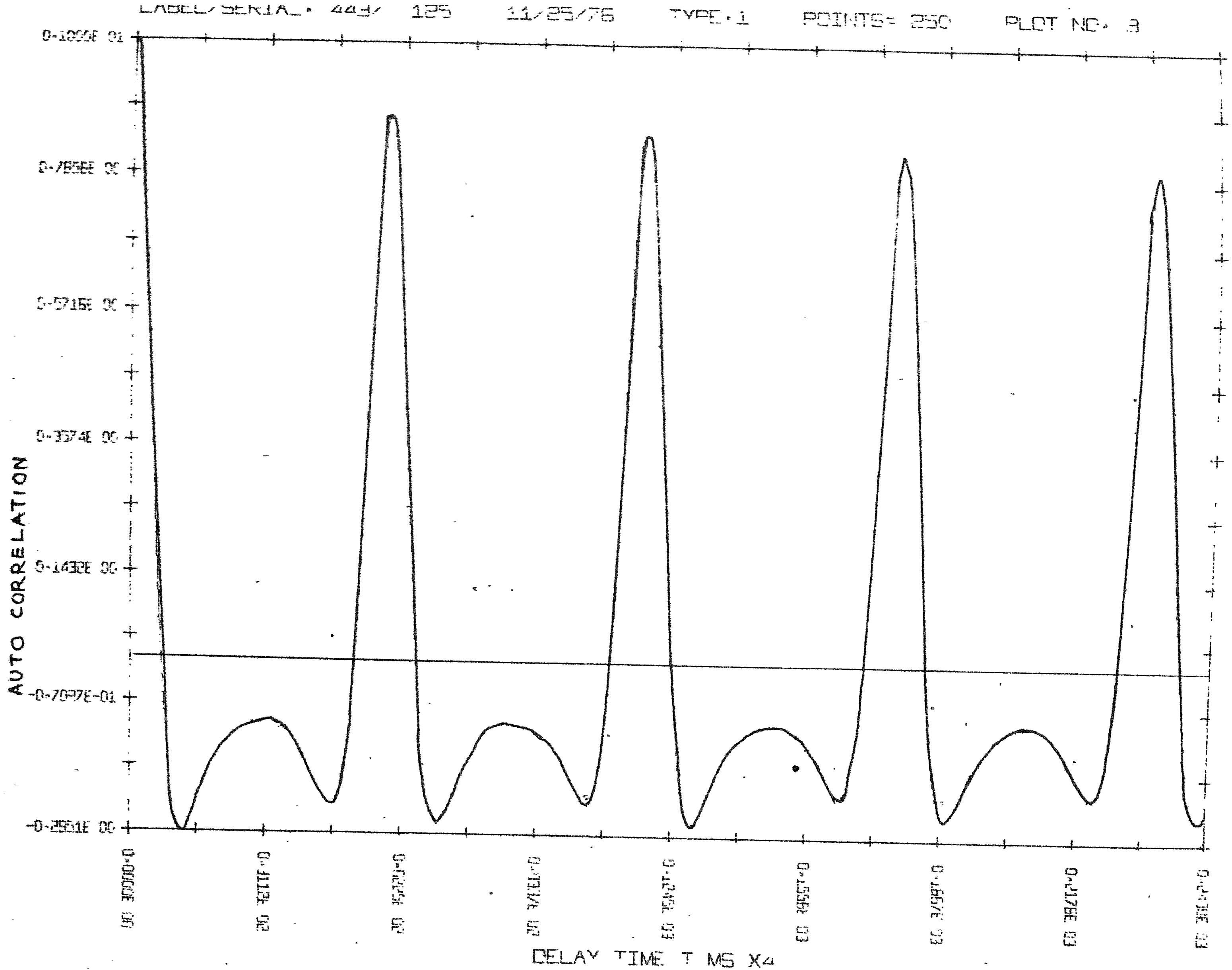

FIG. 4.2a AUTO-CORRELATION, SINGLE BUBBLE, SURFACE TENSION σ_2 11/25/76

CONTROL CARDS FOR EXECUTION OF PROCS - IN IBM 7044

Program PROCS has been put on the tape in RELOAD form. Following control cards are required for executing the program:

Magnetic tape U 437 is input tape

Magnetic tape U 440 is reload tape

Magnetic tape U 443 is output tape

1. Card 1

   $JOB MEG297,TIME065,PAGE8045,NAME

2. Card 2

   Sequence Card

3. Card 3

   $PAUSE MT.U440-B4,U437-C7 BOTH WITHOUT RING,AND U443-ON B9 WITH RING,THANKS.

4. Card 4

	16
$IBJOB	NOSOURCE

5. Card 5

   $RELOAD U04,NAME=PNSNGH,SRCH

6. Card 6

1 -5	6 - 10	11-15	16-20	21-25
LABIN	LABOT	IUNLD	LAST	IWAIT

LABIN : LABEL of input tape, 437

LABOT : Label of output tape, + 443 only for first time,

- 443 for rest of the run.

= 0 OUTPT on tape is not required.

IUNLD := 1, unload the tape

= 0, unloading not required

LAST : Last record on the output tape if

LAST = 0, it is taken as 32000.

IWAIT : 0

7. Card 7

1 - 5	6 - 10	11-15	20-30	51-55
JSER	NLAST	INTVL	JSW	M

CONTINUOUS MODE : For continuous mode of operation two blank cards are needed after Card 6.

SELECTIVE MODE : Card 7.

JSER : Serial number of the data to be processed.

NLAST : Serial number of the last data to be processed.

INTVL : Interval by which the serial number of the data has to be incremented.

JSW : Switches for selecting the output.

Type of Output for Signal:

1 in column 20 for graph

1 in column 22 for paper output

1 in column 24 for punch output

CONTROL CARDS REQUIRED FOR EXECUTION OF P7044

IBM 1800

1. Card 1

   // JOB

2. Card 2

   // XEQ P7044   FX

3. Card 3

   1 - 5   6 - 20

   LABEL   IDATE

LABEL : Label of the tape in I5 format

IDATE : Month, Date, Year in 3I5 format

e.g. 11   29   76

4. Card 4,5

   1-20   21-40

   LABX   LABY

LABX : X-axis label and auto-correlation/spectral density

LABY : Y-axis label and auto-correlation/spectral density

5. Card 6

   1 - 5   6 - 10   11-15

   ISTRT   NLAST   NEWTL

ISTRT : Starting serial number

NLAST : Last serial numper upto which averaging has to be done.

NEWTL : 1, read title card for auto-correlation and

spectral density in 30A2 format in two cards

= 0, no title card

6. Card 7:

Same as card 6

if ISTRT = 0, program calls CALL EXIT.